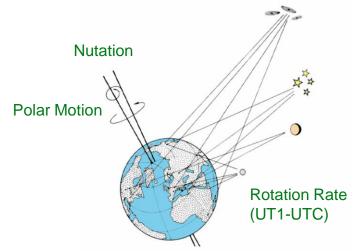# Earth's Time Varying Rotation

Richard Gross

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109–8099, USA

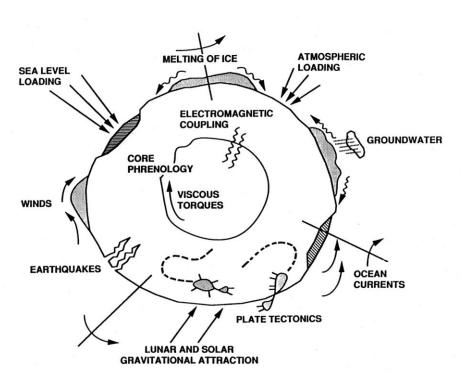Precise Time and Time Interval
Systems and Applications Meeting

January 30, 2017
Monterey, California

Earth Orientation Parameters

- Earth's orientation in space given by 5 parameters:

  - 2 precession-nutation parameters ($\Delta\psi, \Delta\varepsilon$ or X,Y)

    - Specifies location of spin axis in *celestial* reference frame

  - 2 polar motion parameters (PMX, PMY)

    - Specifies location of spin axis in *terrestrial* reference frame

  - 1 spin parameter (UT1)

    - Specifies angle through which Earth has rotated about spin axis

Nutation

Polar Motion

Rotation Rate
(UT1-UTC)

Earth Rotation Dynamics

Sources of Earth Rotation Variations

Rotation of Earth changes

Length of day by few milliseconds

Wobbles by few hundred milliarcsec
(10 meters at North Pole)

Nutation and precession

Rotation changes caused by

External torques — tidal phenomena

Internal deformation — earthquakes,
postglacial rebound

Angular momentum exchange with
bounding fluids — atmosphere,
oceans, core

Studying Earth's rotation improves knowledge of

Rheology and dissipation processes of solid Earth

Interior figure of Earth

Core-mantle coupling

A Brief History of Earth Rotation

Edmond Halley
(1656-1742)

English astronomer

In 1695 Edmond Halley
noted that the Moon is
apparently accelerating
in its orbit

In 1939 Harold Spencer Jones
conclusively demonstrated
that the Earth's rotation
is slowing down

In 1955 atomic clocks provide
uniform timescale for determining
changes in Earth's rate of rotation

EDMVND. HALLEIVS LL.D.
GEOM. PROF. SAVIL. & R.S.SECRET.

Leonhard Euler
(1707-1783)

Swiss mathematician

In 1765 published
*Theoria Motus
Corporum Solidorum*

Predicted Earth
should freely wobble
as it rotates

Period of wobble:
306 days

Seth Carlo Chandler, Jr.
(1846-1913)

American astronomer

In 1891 Chandler observed the free
wobble of the Earth that was
predicted in 1765 by Euler

Period of observed wobble:
427 days

Later in 1891 Simon Newcomb
explained difference between
prediction and observation
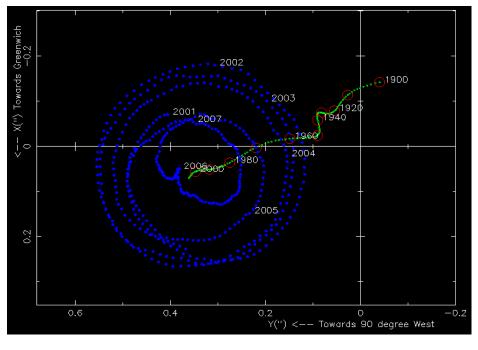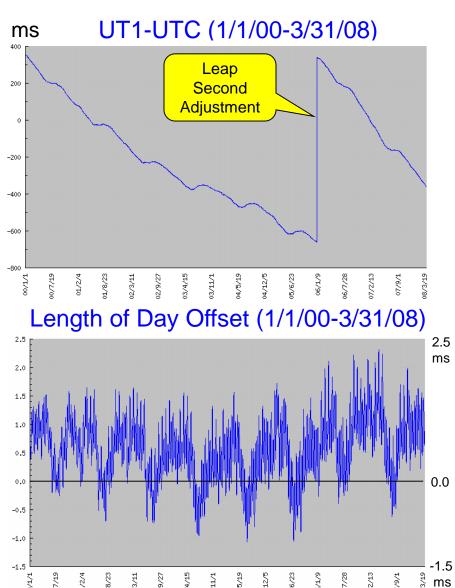as due to "elasticity of the Earth"
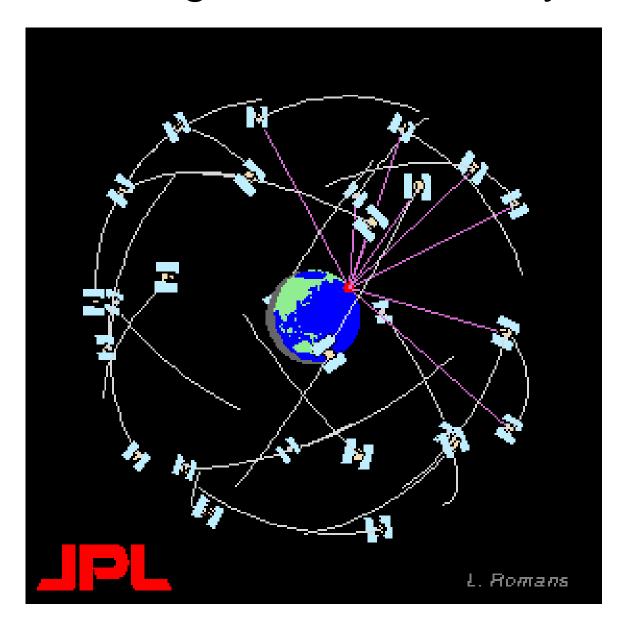and "fluidity of the ocean"

Observations

Observed Earth Rotation Variations

Polar Motion
2001-2007 and
mean pole since 1900

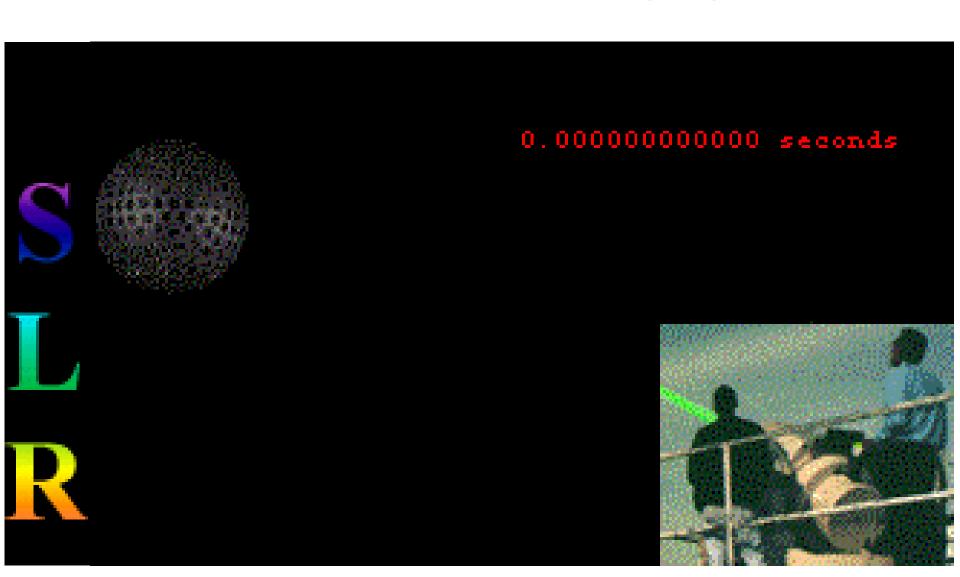UT1-UTC (1/1/00-3/31/08)

Leap Second Adjustment

Length of Day Offset (1/1/00-3/31/08)

Global Navigation Satellite Systems

L. Romans

Satellite Laser Ranging

Interpretation

Mass Transport in the Earth System

Ilk et al. (2005)

Forcing Mechanisms

- External
  - Tidal potential
    - Body, ocean, atmosphere
- Surficial
  - Atmospheric winds and surface pressure
  - Oceanic currents and bottom pressure
  - Water stored on land (liquid, snow, ice)
- Internal
  - Earthquakes and tectonic motions
  - Mantle convection
  - Outer core dynamics / coupling with mantle
  - Inner core dynamics / coupling with outer core and mantle

Geodetic Measures of Earth's Response

- ## Rotation
  - Angular momentum exchange (surface fluids, outer core)
  - Torques (external, surficial, internal)
  - Changes in inertia tensor (earthquakes, GIA)

- ## Gravity and geocenter
  - Mass distribution (static field)
  - Mass redistribution (time varying field)
  - Surface displacements (ground-based)

- ## Shape
  - Tidal displacements
  - Surface loading and unloading
  - Internal deformation
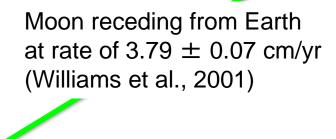   - Earthquakes, core pressure => mantle deformation
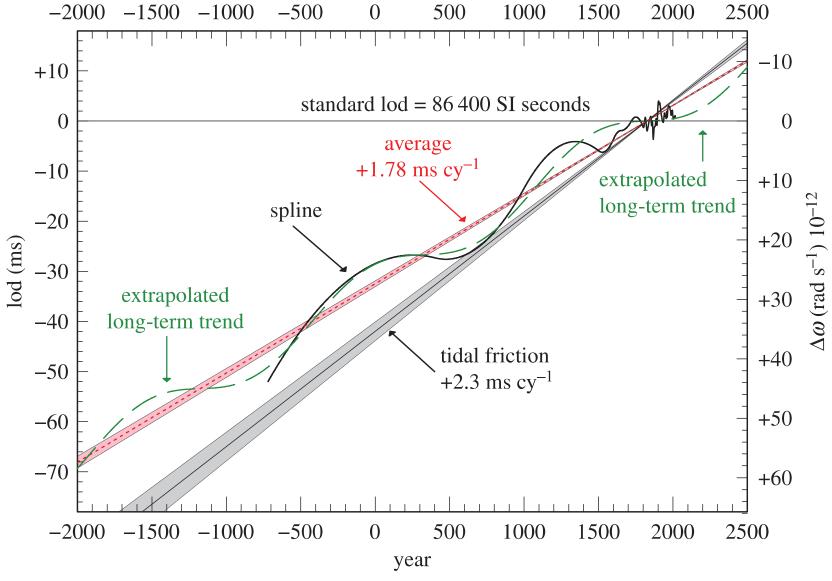
Tidal Variations: Dissipation

APOLLO station ranging to Moon. Source: Dan Long

Lunar Recession

Moon receding from Earth
at rate of 3.79 $\pm$ 0.07 cm/yr
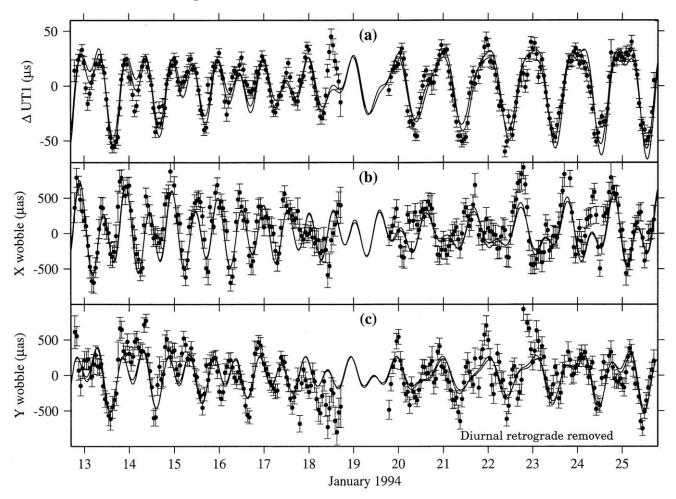(Williams et al., 2001)

Secular change in the length-of-day from −2000 to +2500 estimated from lunar and solar eclipse, lunar occultation, optical astrometric, and space-geodetic observations. The difference between the observed secular trend (shaded red) and that caused by tidal friction (shaded grey) is due to the effects of glacial isostatic adjustment and other processes such as ice sheet mass change and the accompanying nonsteric change in sea level. From Stephenson, Morrison and Hohenkerk (2016).

Tidal Variations: Subdaily

Subdaily Earth Orientation Variations

Plots of observed and modeled (a) UT1, (b) *x*-component of polar motion, and (c) *y*-component of polar motion during the Cont94 measurement campaign of January 12–26, 1994. The dots with 1σ error bars are the hourly VLBI observations. Polar motion variations in the retrograde nearly diurnal frequency band have been removed from the observed series and are not included in the modeled series. The solid lines are the predicted effects from the diurnal and semidiurnal T/P ocean tide models B and C of Chao *et al.* (1996). Each tide model explains about 90% of the observed UT1 variance and about 60% of the observed polar motion variance. From Chao et al. (1996).

Tidal Variations: Long-Period
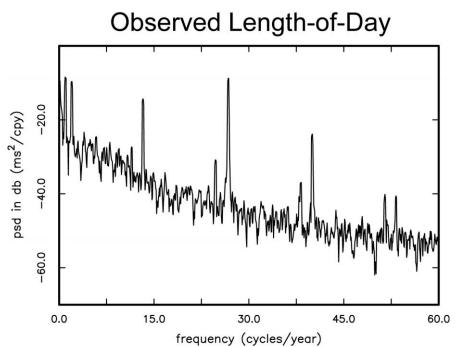
Observed Length-of-Day

Observed Length-of-Day

Remove AAM & OAM
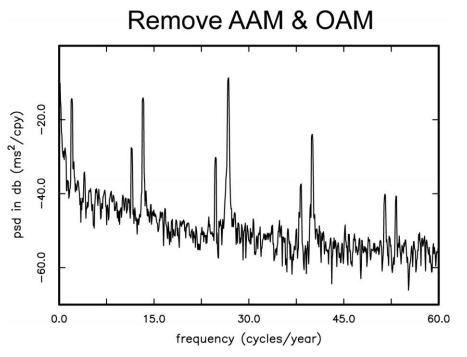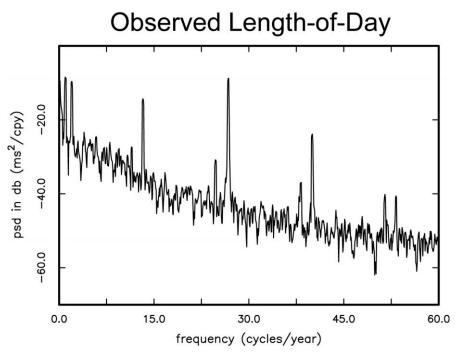
Observed Length-of-Day

Remove Solid BodyTides

Remove AAM & OAM

Observed Length-of-Day

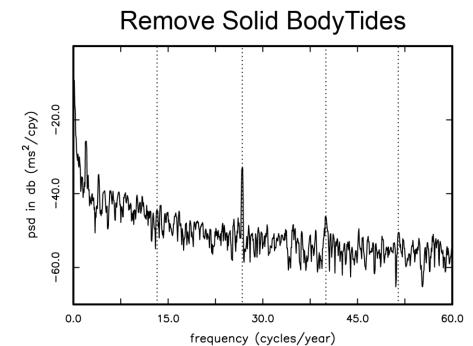**Remove Solid BodyTides**

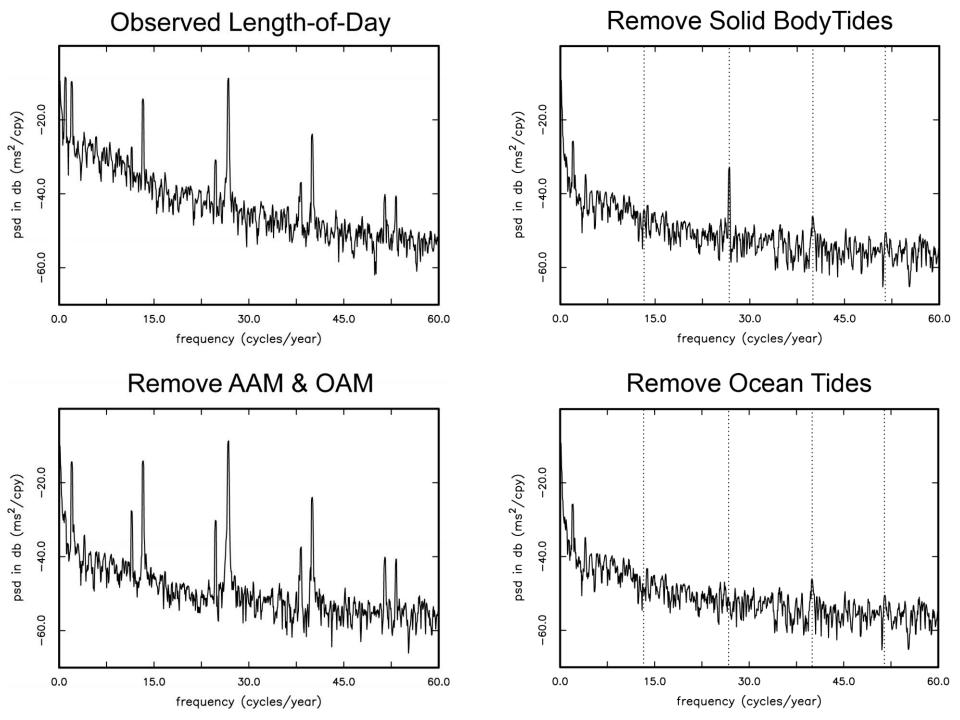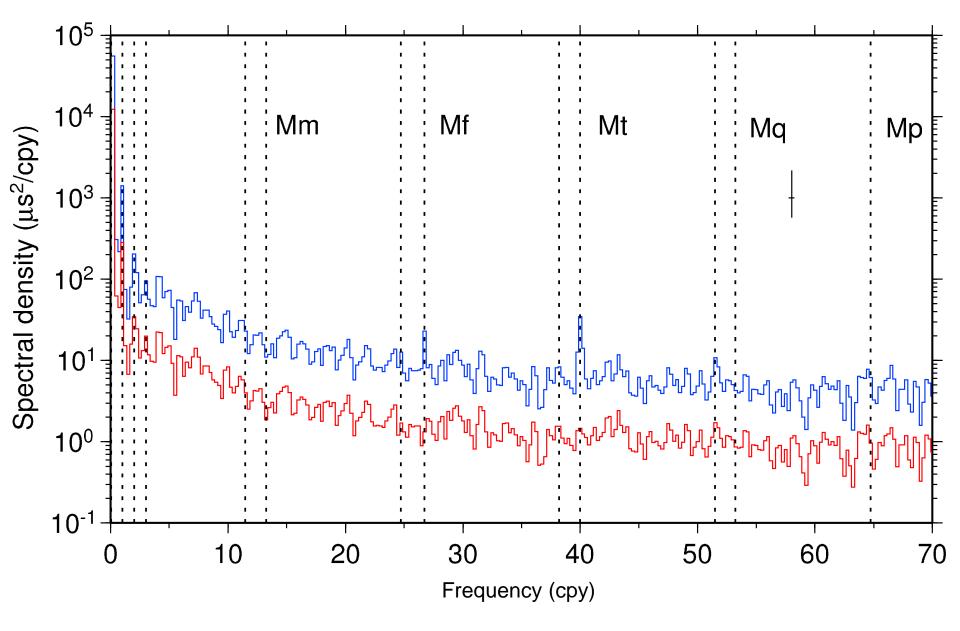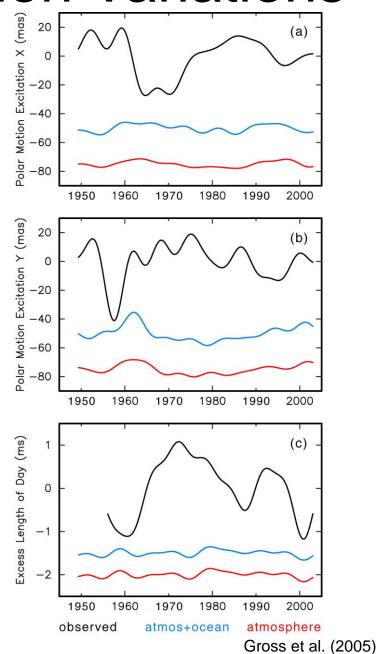**Remove AAM & OAM**

Remove Ocean Tides
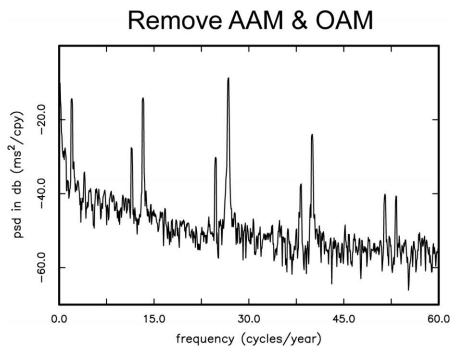
Residual spectrum of LOD after removing all geophysical models, including tides. Blue line is based on using the long-period LOD tide model in the 2010 IERS Conventions. Red line is based on using the model of Ray and Erofeeva (2014). From Ray and Erofeeva (2014).
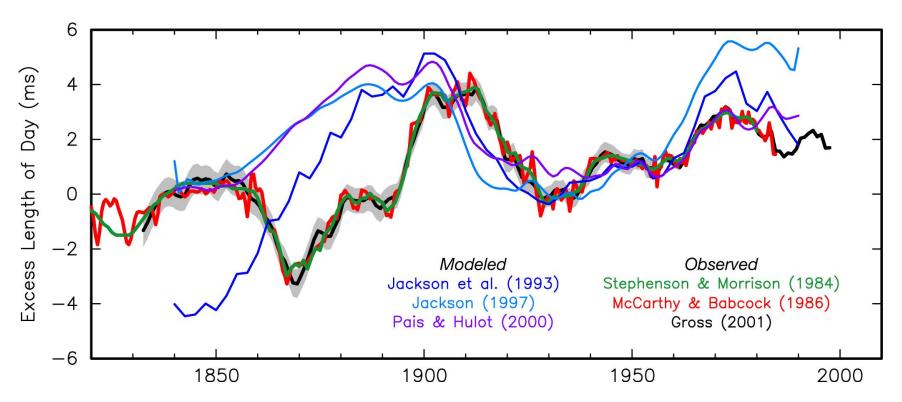
Non-Tidal Variations: Decadal

Decadal Earth Rotation Variations

- ## Observed excitation
  - ### Extended COMB2002
    - Combination of optical astrometric, LLR, SLR, VLBI, and GPS measurements
    - Spans 1948–2002 at daily intervals (UT1 and LOD since 1956)

- ## Atmospheric excitation
  - ### NCEP/NCAR reanalysis AAM
    - Sum of wind and i.b. pressure terms
    - Spans 1948 to present at 6-hour intervals

- ## Oceanic excitation
  - ### ECCO/JPL 50-year OAM
    - Sum of current and bottom pressure terms
    - Spans 1949–2002 at 10-day intervals

- ## Detrended & low pass filtered
    - Cutoff period of 6 years

observed   atmos+ocean   atmosphere

Gross et al. (2005)

Decadal Variations

Plots of observed and modeled length-of-day variations on decadal time scales. The observed LOD series are those of Gross (2001; 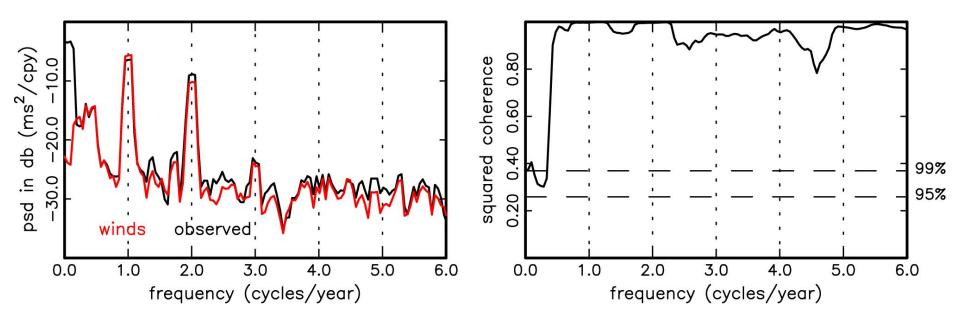black curve with gray shading representing ± 1σ standard error), McCarthy and Babcock (1986; red curve), and Stephenson and Morrison (1984; green curve). Note that after about 1955 the uncertainties of the Gross (2001) LOD values are less than the width of the black line. The modeled core angular momentum series are those of Jackson *et al.* (1993; dark blue curve), the *uvm-s* model of Jackson (1997; light blue curve), and the PH-inversion model of Pais and Hulot (2000; purple curve). A secular trend of +1.8 ms/cy has been added to the modeled core angular momentum series to match the observed secular trend. An arbitrary bias has also been added to the modeled series in order to facilitate their comparison with the observed series.

Gross (2015)
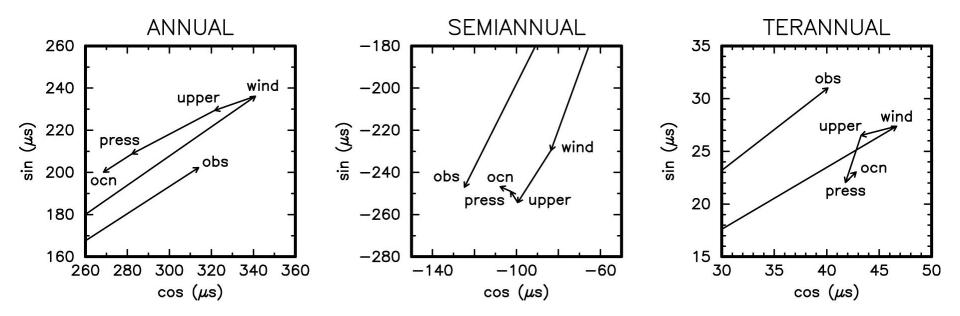
Non-Tidal Variations: Sub-Decadal

Sub-Decadal Variations
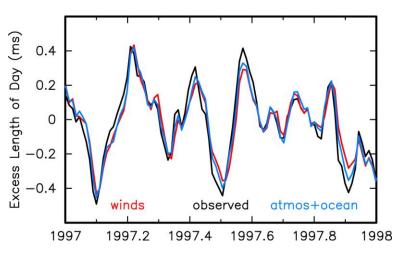
Power spectra (left panel) and squared magnitude of the coherence (right panel) of the observed length-of-day variations during 1980–2000 and those due to atmospheric winds below 10 hPa. The power spectral density (psd) estimates in the left panel, given in decibels (db), were computed by the multitaper method with the spectrum of the observed variations shown in black and that due to the winds shown in red. The horizontal dashed lines in the right panel indicate the 95% and 99% confidence levels of the squared magnitude of the coherence between the observed and wind-driven LOD variations.

Gross et al. (2004)

Seasonal Variations

Phasor diagrams of the annual (left panel), semiannual (middle panel), and terannual (right panel) components of the observed length-of-day variations (obs) during 1992–2000 and of the effects on the LOD during this time period of atmospheric winds below 10 hPa (wind), winds above 10 hPa (upper), surface pressure (press), and the oceans (ocn). The atmospheric surface pressure term was computed by assuming that the oceans respond as an inverted barometer to the imposed surface pressure variations. The oceanic results include the effects of both currents and ocean-bottom pressure. The reference date for the phase is January 1.0, 1990 which in the diagram is measured counterclockwise starting from a horizontal position. Note the change in scale of the terannual phasor diagram.

Gross et al. (2004)
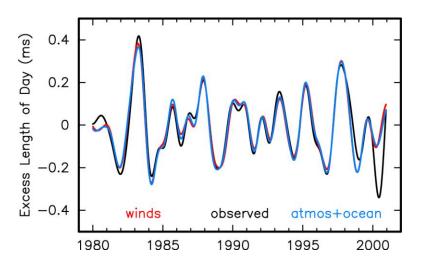
Intraseasonal Variations

Observed length-of-day variations (black); variations caused by the modeled atmospheric winds (red); and variations caused by the sum of the modeled atmospheric winds, surface pressure, oceanic currents, and bottom pressure (blue) on intraseasonal time scales during 1997. Intraseasonal variations considered here have periods ranging between 4 days and 1 year excluding signals at the annual, semiannual, and terannual frequencies. The atmospheric surface pressure term is that computed assuming the oceans respond as an inverted barometer to the imposed surface pressure variations. The contribution to intraseasonal LOD variations of the winds between 10 hPa and 0.3 hPa is included in the red and blue curves. The mean has been removed from all series.

Excitation process	Variance explained	Correlation
Atmospheric		
winds (ground to 10 hPa)	85.8%	0.93
winds (10 hPa to 0.3 hPa)	1.1%	0.12
all winds (ground to 0.3 hPa)	85.9%	0.93
surface pressure (i.b.)	3.3%	0.18
all winds and surface pressure (i.b.)	90.2%	0.95
Oceanic		
currents	4.1%	0.36
bottom pressure	3.3%	0.30
currents and bottom pressure	7.0%	0.36
Atmospheric and oceanic		
all winds and currents	87.4%	0.94
surface (i.b.) and bottom pressure	5.9%	0.25
Total of all atmospheric and oceanic		
w/o winds above 10 hPa	91.9%	0.96
with winds above 10 hPa	92.2%	0.96

%, percentage; i.b., inverted barometer; w/o, without; 99% significance level for correlations is 0.18; intraseasonal variations considered here have periods ranging between 4 days and 1 year excluding signals at the annual, semiannual, and terannual frequencies

Gross et al. (2004)
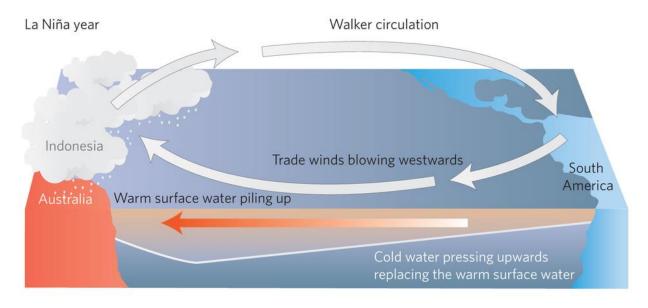
Interannual Variations

Observed length-of-day variations (black); variations caused by the modeled atmospheric winds (red); and variations caused by the sum of the modeled atmospheric winds, surface pressure, oceanic currents, and ocean-bottom pressure (blue) on interannual time scales during 1980–2000. The interannual frequency band ranges from 1/5 cpy to 1 cpy. The atmospheric surface pressure term is that computed assuming the oceans respond as an inverted barometer to the imposed surface pressure variations. The mean has been removed from all series.
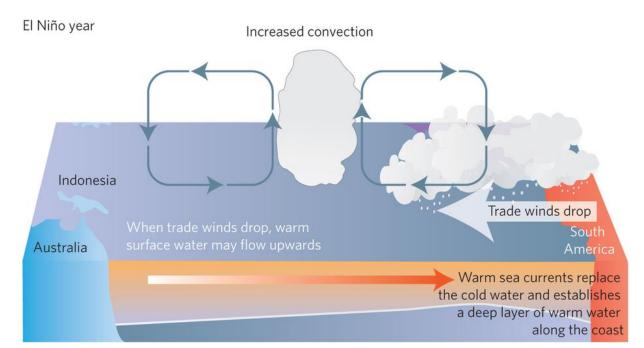
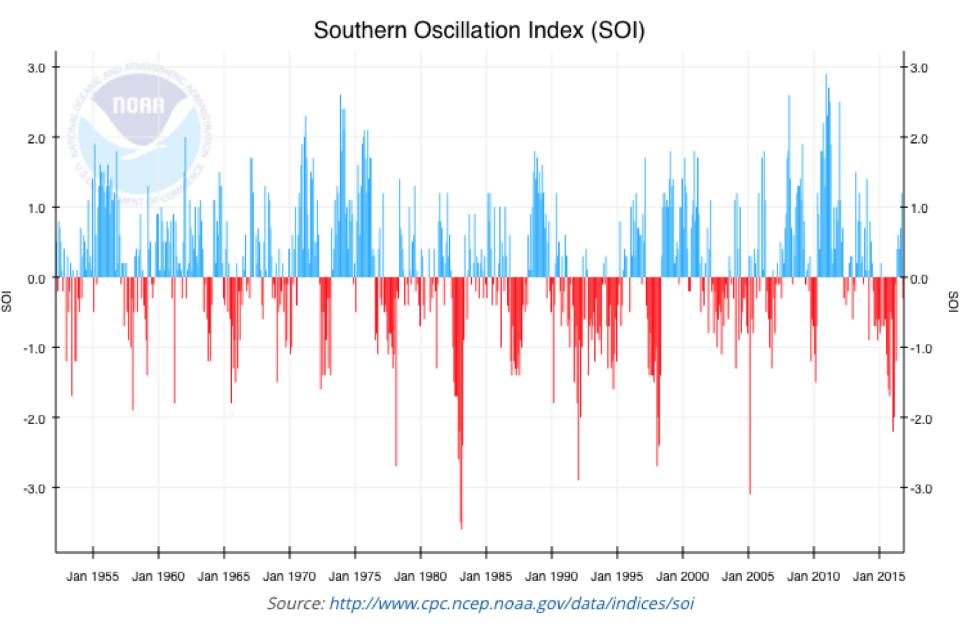| Excitation process	Variance explained	Correlation
Atmospheric		
winds (ground to 10 hPa)	85.8%	0.93
surface pressure (i.b.)	2.6%	0.24
winds and surface pressure (i.b.)	87.3%	0.93
Oceanic		
currents	0.6%	0.14
bottom pressure	0.4%	0.09
currents and bottom pressure	0.8%	0.12
Atmospheric and oceanic		
winds and currents	86.2%	0.93
surface (i.b.) and bottom pressure	2.9%	0.23
Total of all atmospheric and oceanic	87.9%	0.94

%, percentage; i.b., inverted barometer; 99% significance level for correlations is 0.38; interannual frequency band ranges from 1/5 cpy to 1 cpy

Gross et al. (2004)

Interannual Variations and El Niño / Southern Oscillation

The El Niño / Southern Oscillation

(Heffernan, 2014)

Southern Oscillation Index (SOI)
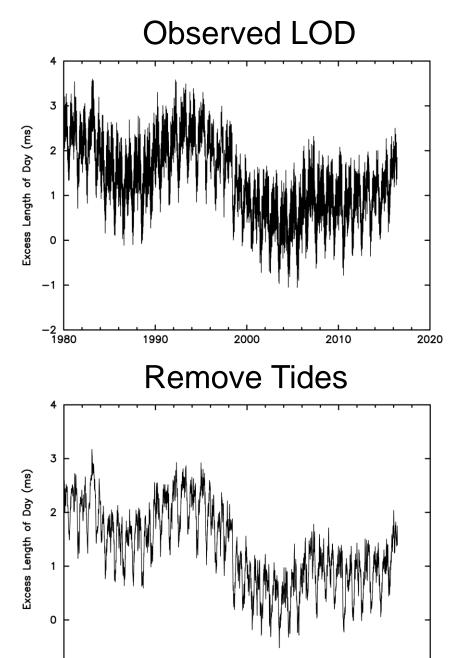
Source: http://www.cpc.ncep.noaa.gov/data/indices/soi

SOI: Standardized difference in (Tahiti – Darwin) sea level pressure anomalies
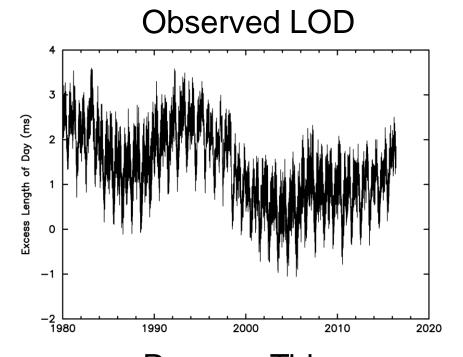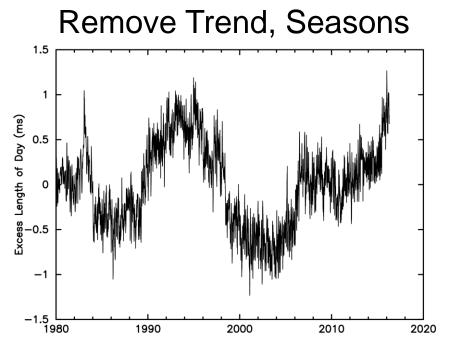
ENSO and LOD

- ## During an El Niño / Southern Oscillation event
  - ### Southern Oscillation Index decreases
    - Standardized difference in (Tahiti – Darwin) sea level pressure anomalies decreases
  - ### Tropical easterlies collapse
    - Atmospheric angular momentum due to winds increases
    - Solid Earth's angular momentum decreases
    - Length of day increases

- ## Investigate effect of 2015–2016 ENSO on LOD
  - ### Compare observations of LOD to models of AAM
    - In interannual frequency band
    - After removing tidal signals from LOD

Observed LOD

Observed LOD

Remove Tides

Observed LOD

Remove Trend, Seasons

Remove Tides

Observed LOD — Remove Trend, Seasons — Remove Tides — Interannual LOD

Interannual Length-of-Day

Interannual Length-of-Day

Interannual Length-of-Day

Interannual Length-of-Day

Interannual Length-of-Day
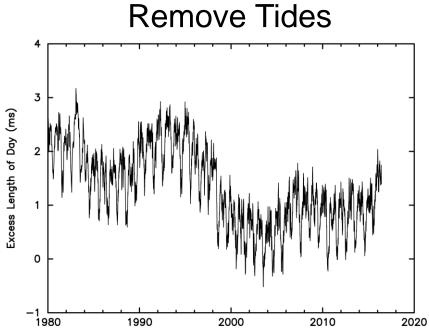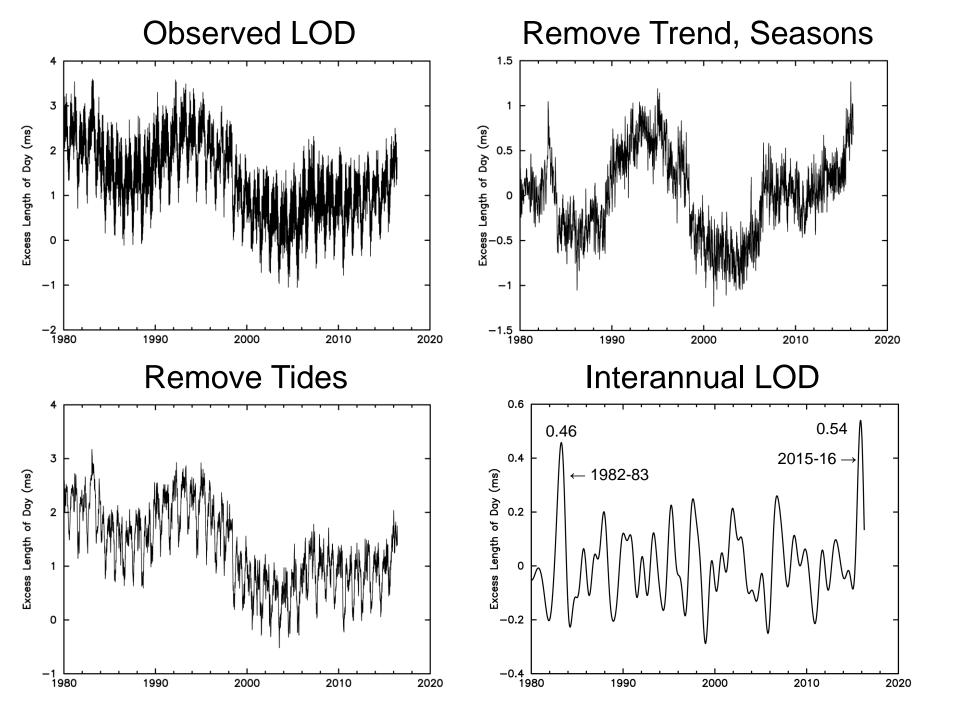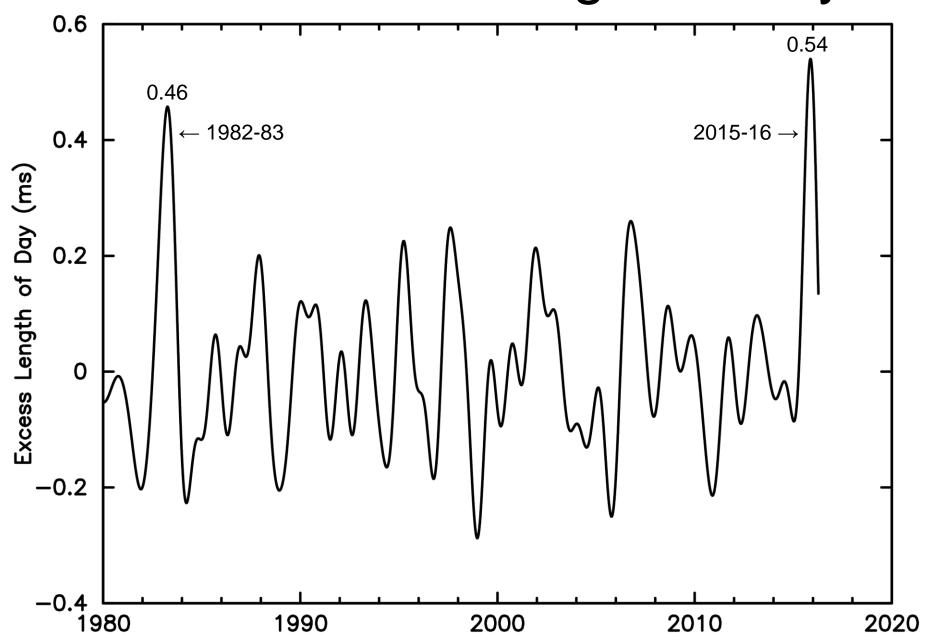
Navigating Interplanetary Spacecraft

Introduction

- Accurate navigation of interplanetary spacecraft requires accurate knowledge of Earth's orientation

  - Must know Earth's orientation in space to know spacecraft's position in space from Earth-based tracking measurements

    - Uncertainty in Earth's orientation can be a major, if not the dominant, source of error in spacecraft navigation and tracking (Estefan and Folkner, 1995)
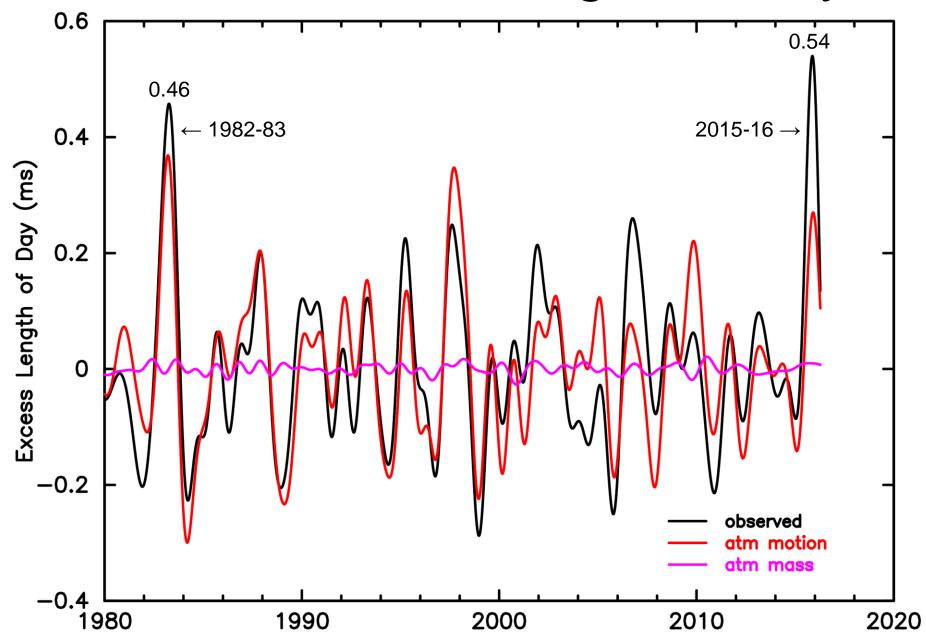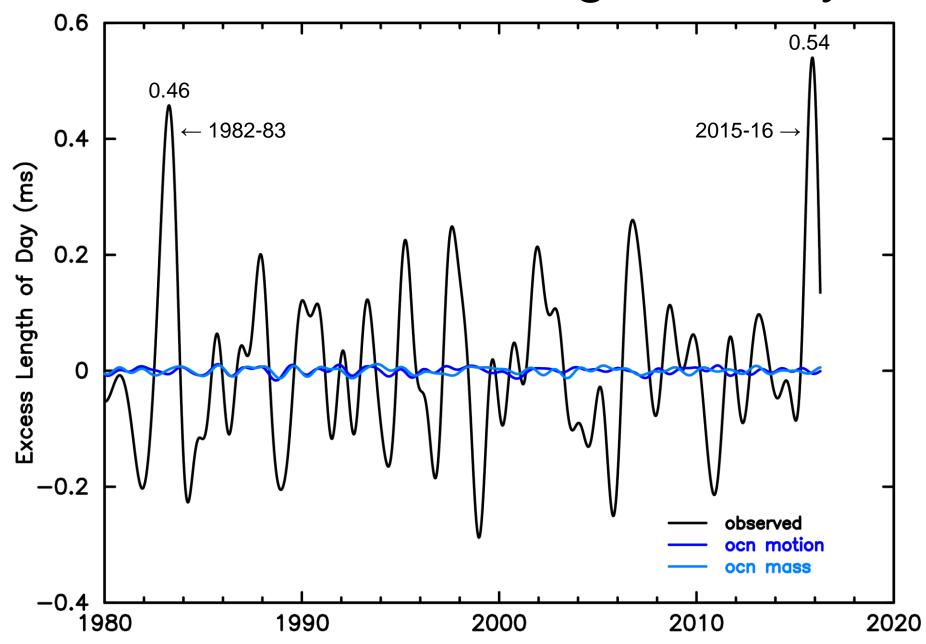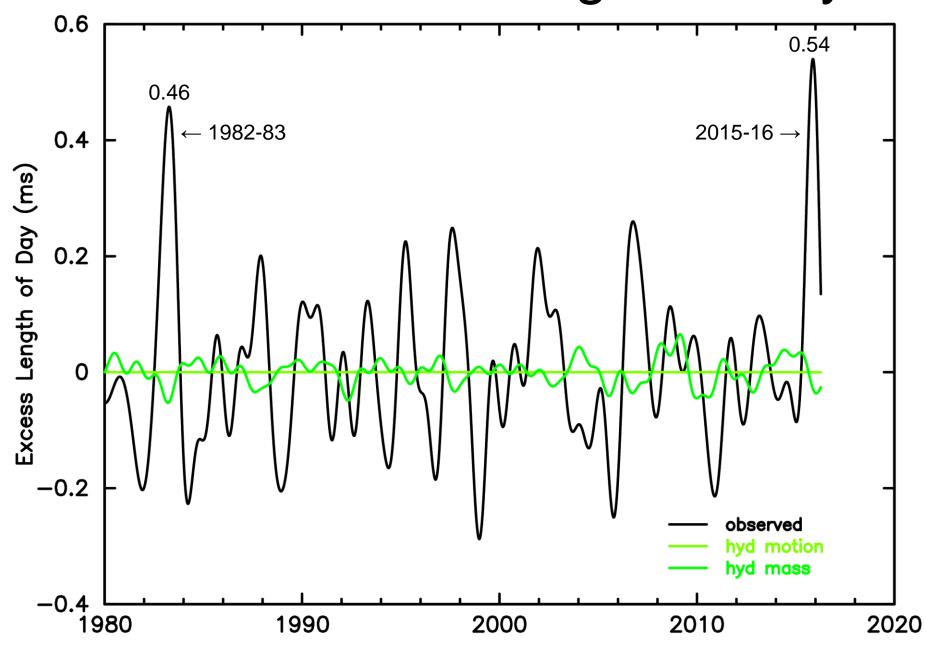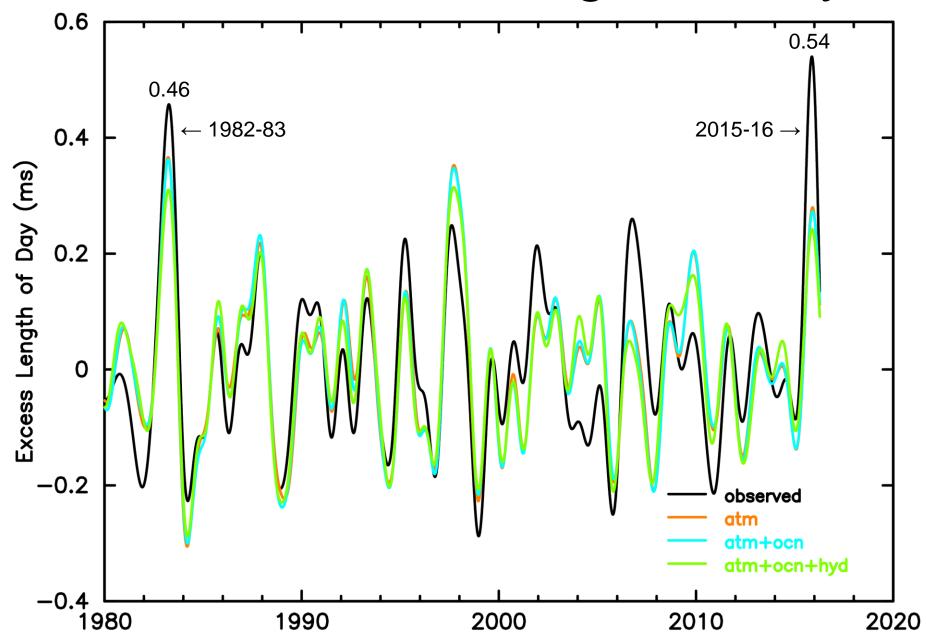
    - Error in UT1 of 0.1 ms (4.6 cm) produces an error of 7 nrad in spacecraft right ascension, corresponding to a position error at Mars of 1.6 km

- Earth's orientation in space given by 5 parameters:

  - 2 precession-nutation parameters ($\Delta\psi, \Delta\varepsilon$ or X,Y)

    - Specifies location of spin axis in *celestial* reference frame

  - 2 polar motion parameters (PMX, PMY)

    - Specifies location of spin axis in t*errestrial* reference frame

  - 1 spin parameter (UT1)

    - Specifies angle through which Earth has rotated about spin axis

Introduction, cont.

- Earth's orientation varies rapidly and unpredictably
  - UT1 variations are particularly difficult to predict
    - Rapid UT1 variations caused mainly by changes in angular momentum of winds
    - Predicting UT1 is as challenging as predicting the weather
  - In contrast, precession-nutation can be accurately modeled
    - Precession-nutation caused by gravitational attraction of Sun, Moon, & planets
    - Model predictions rely upon past measurements
- Measurements of UT1 and polar motion must be taken frequently and processed rapidly to maintain a real-time knowledge of the Earth's orientation:
  - Tracking and Navigation Service Requirements
    - 30 cm (1 sigma) in real time
    - 5 cm (1 sigma) for a posteriori reconstructions after 14 days
  - Demanding missions request much tighter accuracies
    - 2 cm real-time polar motion and 5 cm real-time UT1 for Phoenix

Earth Orientation Measurements

- Determine the full set of UT1 and polar motion
  - Multibaseline VLBI

- Determine a subset of UT1 and polar motion
  - Single baseline VLBI (Intensives)

- Determine linear combinations of UT1 and PM
  - Single baseline VLBI determines transverse, vertical
  - Single station LLR determines UT0, variation-of-latitude

- Are irregularly spaced in time, vary in accuracy, and may be corrupted by systematic errors
  - GPS LOD measurements include errors arising from motion of GPS satellite constellation

- Design of KEOF dictated by these characteristics of the Earth orientation measurements

Earth Orientation Data

- ## Internal data
  - ### GPS Quick-Look measurements (PMX, PMY, UT1 rate)
    - Acquired daily, subdaily latency
  - ### TEMPO single baseline VLBI measurements (UT0)
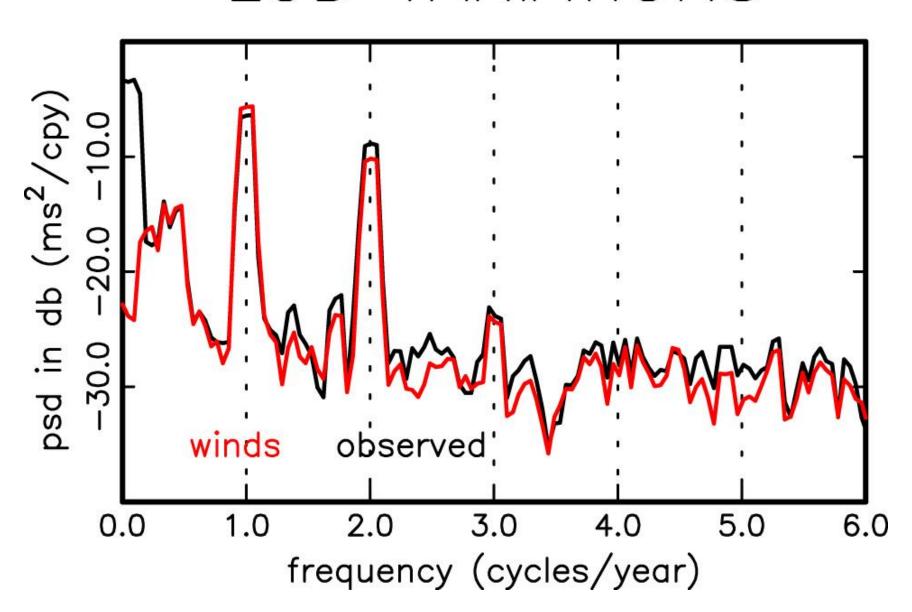   - Acquired twice-per-month, 1-week latency
- ## External data
  - ### Inertial sources
    - Very long baseline interferometry (Intensive UT1 – acquired daily, 2-day latency)
    - Very long baseline interferometry (Multibaseline – few times/wk, 2-week latency)
    - Lunar laser ranging (acquired irregularly, subdaily latency)
  - ### Non-inertial sources
    - Satellite laser ranging (ILRS Combined – acquired daily, 1-week latency)
    - Global positioning system (IGS Rapids – acquired daily, subdaily latency)
    - Global positioning system (IGS Finals – acquired daily, 2-week latency)
  - ### Proxy length of day (UT1 rate) data
    - Atmospheric angular momentum analyses (acquired daily, subdaily latency)
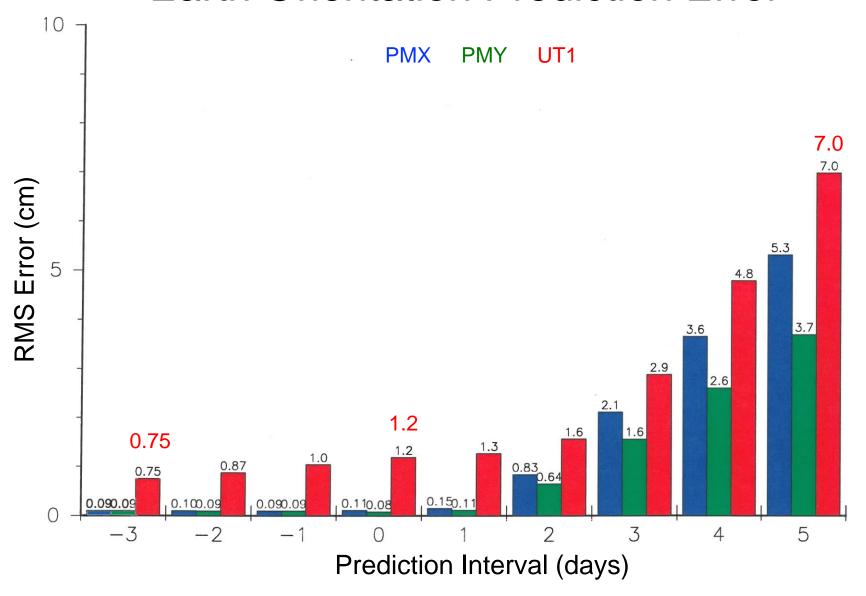   - Atmospheric angular momentum dynamical forecasts (daily, 7.5 days into future)

LOD VARIATIONS

(Gross et al., 2004)

Kalman Filter

- A Kalman filter is well-suited to combining irregularly spaced, incomplete and/or degenerate measurements of varying accuracy subject to systematic errors

- Information matrix approach allows use of measurements spanning arbitrary subspace of UTPM parameter space

  - Information matrix is zero for that subspace of UTPM space not spanned by the measurements

  - Measurements do not need to be of only polar motion and/or UT1

- State vector is propagated to arbitrary time of measurement

  - Measurements do not need to be taken at the same time

- Measurement vector is combined with propagated state vector by vector-weighted average

  - Measurement uncertainties used as weights when combining data

  - Measurement correlations are taken into account

- Stochastic models of process and measurement noise are included

  - Allows systematic errors to be modeled

    - Such as effect of GPS satellite constellation motion on GPS LOD measurement
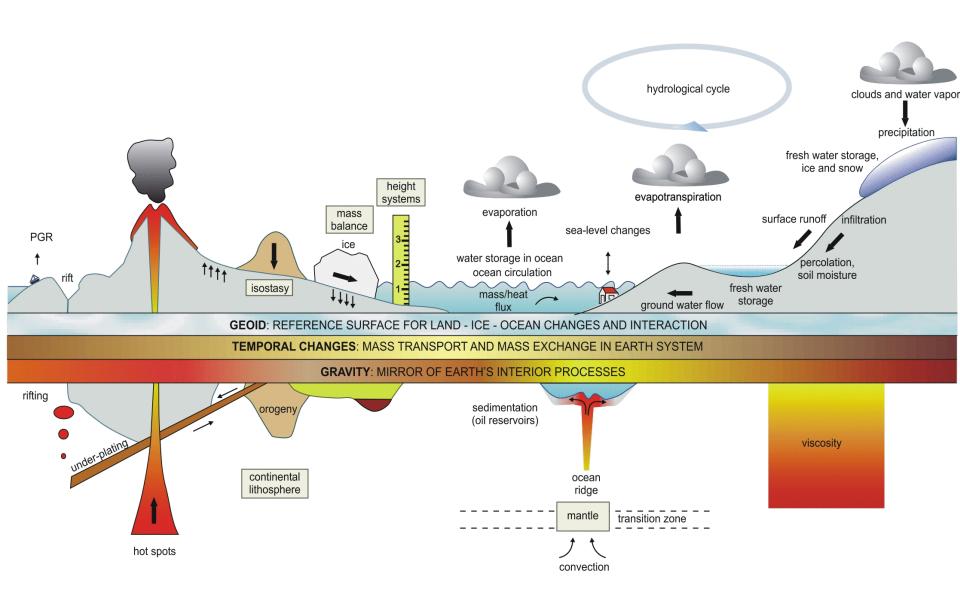
  - Enables use of proxy measurements such as AAM

Earth Orientation Prediction Error

Prediction day 0 is epoch of file generation and delivery
180 Deliveries Spanning July 1, 2014 to December 31, 2014

Summary

Mass Transport in the Earth System

Ilk et al. (2005)

Forcing Mechanisms

- External
  - Tidal potential
    - Body, ocean, atmosphere

- Surficial
  - Atmospheric winds and surface pressure
  - Oceanic currents and bottom pressure
  - Water stored on land (liquid, snow, ice)

- Internal
  - Earthquakes and tectonic motions
  - Mantle convection
  - Outer core dynamics / coupling with mantle
  - Inner core dynamics / coupling with outer core and mantle

Geodetic Measures of Earth's Response

- ## Rotation
  - Angular momentum exchange (surface fluids, outer core)
  - Torques (external, surficial, internal)
  - Changes in inertia tensor (earthquakes, GIA)

- ## Gravity and geocenter
  - Mass distribution (static field)
  - Mass redistribution (time varying field)
  - Surface displacements (ground-based)

- ## Shape
  - Tidal displacements
  - Surface loading and unloading
  - Internal deformation
    - Earthquakes, core pressure => mantle deformation

Selected Scientific Questions

- Climate change
  - Global warming
    - Atmosphere, oceans, Earth surface
- Ice mass balance / sea level change
  - Mountain glaciers, grounded and floating ice sheets
- Natural hazards
  - Earthquakes, volcanoes, landslides, tsunamis
- Earth structure
  - Interior figure, mantle anelasticity, 3D mass distribution
- Mantle and core dynamics
  - Coupling mechanisms
- Origin of observed variations
  - Earth rotation, gravity and geocenter, shape

Pathways to Advancement

- **Improved measurements**
  - Accuracy, temporal resolution, duration
- **Improved models**
  - Forcing mechanisms
    - Atmosphere, oceans, hydrology, core
  - Earth's response to forcing
    - Anelastic effects
- **Improved theory**
  - Higher order
  - Dynamic oceans and core
  - Core-mantle coupling
- **Consistent computations**
  - Love numbers